Modeling and Performance Metrics for Longitudinal Chromatic Aberrations, Focus-drilling, and Z-noise; Exploring excimer laser pulse-spectra

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ABSTRACT

The combined impact of longitudinal chromatic aberrations, focus-drilling, and Z-noise on several lithographic performance metrics is described. After review, we investigate an improved method for simulating the lithographic behavior of longitudinal chromatic aberrations stemming from the finite bandwidth of excimer laser pulse-spectra[1] using PROLITH™ v. 9.3.3. Additionally, we explore two methods for modeling the lithographic improvements related to focus-drilling and new PROLITH functionality for modeling the effects of Z-noise. Our case studies involve re-investigating the RELAX[2] process and providing a framework for accurate lithographic simulation using machine specific pulse-spectral data, modified Lorentzian, and Gaussian models. After presentation and analysis, we discuss potential applications including methods for improved focus budgets and improved mask design.

Keywords: aberration, chromatic, CDP, DFM, EFESE excimer, focus, laser, longitudinal, lithography, modeling, noise, optics, OPC, pulse, scanner, simulation, spectra.

1. INTRODUCTION

For this work, we investigate improved methods for simulating the lithographic behavior of longitudinal chromatic aberrations (Figure 1) stemming from the finite bandwidth of excimer laser pulse-spectra[1, 3] using PROLITH™ v. 9.3.3. We also introduce new methods for simulating focus-drilling operations in the presence of scanner noise using actual excimer laser spectral data. Our topic is important for several deep-UV lithographic applications including TCAD and DFM methodologies where design tolerances for complex (OPC and PSM) mask design will approach 1nm at the 45nm technology node[4]. Additionally, those of us who are working in a foundry-oriented manufacturing environment now realize that accurate and high-speed lithographic simulation is a necessity for applying wavefront corrections correctly the first time since the cost of mask sets at the 65nm node is now approaching 5 million dollars[5]. As our industry pushes the limits of optical lithography we find it necessary to continuously improve our lithographic models to account for subtle lithographic behavior in our attempt to mimic the lithographic process – thus the need for accurate scanner/laser metrology, spectral inputs for lithographic simulation, and rigorous mask simulation.

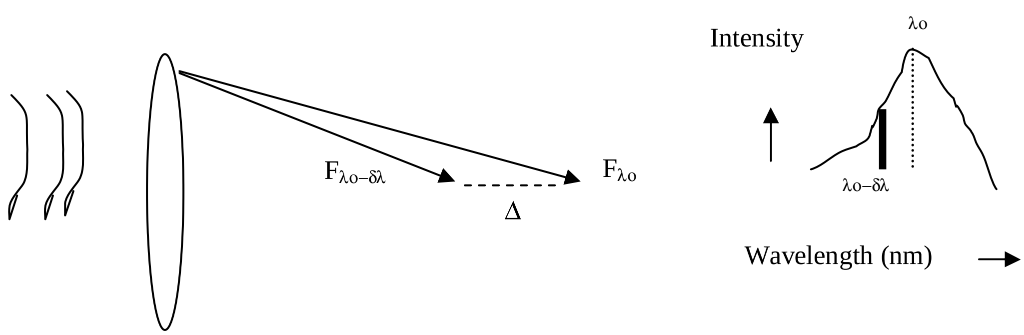

Figure 1: Projection lens system and illumination spectral plot

1.1 Longitudinal Chromatic Aberrations (LCAs)

One of the most accurate ways of quantifying chromatic aberrations (all of them) would be to measure lens aberrations as a function of wavelength and field position using a tool such as the Litel Instruments ISI[6, 7] and then create a complete set of Zernike coefficients for each wavelength and field point of interest. In the absence of such information, one can approximate the lithographic effects due to chromatic aberrations alone (longitudinal) by assigning a focus error or offset (Δ in Figure 1 above) for each small portion of the illumination spectrum that is different from nominal (Figure 1 above) – then, weighting and summing the effects of each small portion during simulation. For this work, we focus on the effects of longitudinal chromatic aberrations as compared to other (higher order) chromatic aberrations (such as lateral chromatic) because for both 248nm and 193nm lenses focus-shift with wavelength dominates[7]. The lithographic effects associated with exposing wafers using excimer laser pulses with finite bandwidths (producing semi-symmetrical longitudinal and lateral chromatic aberrations) are probably best described by the papers from both Intel[8] and Cymer[1,9] (where the preferred metric for predicting lithographic performance is E95 rather than Full Width at Half Max or FWHM). For review, when simulating the effects of longitudinal chromatic aberrations using Lorentzian or actual excimer laser spectra each thin slice of the illumination spectra different from nominal produces an out-of-focus contribution to the resultant field distribution with a magnitude determined by the chromatic slope (nm/pm) or rate-of-defocus, which is different for each optical system.

In the past, PROLITH users created both an illumination spectrum file (.ill) and matching wavelength-aberration file (.zrn) to simulate the effects of longitudinal and other chromatic aberrations. For LCAs, lithographers typically only consider *lithographers defocus* (Zernike Z4 with no spherical terms) when calculating/assigning the phase error for each longitudinal chromatic focus offset (Δ); using the following first order equation (Equation 1) for Zernike defocus:

Equation 1: $$Z_4 = \Delta * NA^2 / 4 * \lambda_0 n$$

where Δ, the focus error for each slice of the illumination spectrum is equal to the product of the chromatic aberration slope (Λ nm/pm also known as “Rate of Defocus” in PROLITH) and the net offset (+/-) from center wavelength (λo in pm), and n is the refractive index of the immersion liquid (n=1 for “dry” systems and n=1.44 for ArF immersion systems) With today’s high NA systems, the complete “cosine” phase error term is certainly important and is now automatically calculated by simply selecting a laser spectrum (.ill) and a chromatic aberration slope in PROLITH v. 9.3.3. Additionally, with the main speed factor set equal to -1, PROLITH v. 9.3.3 automatically calculates the longitudinal chromatic error for ***each*** wavelength (thin slice) in the illumination spectrum (up to 4000 spectral points) and then adds the aerial images together (a superposition) using a weight determined by the illumination spectrum.

2. METHODS

2.1 Excimer pulse-spectra (EPS)

Today, Cymer reports that excimer bandwidths (FWHM) are of the order ~0.12pm for 193nm exposure systems. Over the last several years Cymer has shown that the E95 metric (~0.29pm for 193nm systems) is a more relevant metric[9] for predicting lithography performance. Since PROLITH v. 9.3.3 now includes actual CYMER excimer spectra (.ill, illumination files) it might be a good time to review how one obtains the actual spectra and what it represents (for several interesting reasons). It is not obvious (even to most seasoned lithographers) how to describe the actual spectrum of light that exposes resist patterns using a scanner system and excimer laser and a bit of elaboration on the subject might prove helpful here. While some technical papers discuss excimer operation[10] few give the details on how to obtain the actual laser spectra that best represent the exposure conditions on the wafer. Since modern excimer lasers deliver short bursts of pulses (at kHz frequencies) of near monochromatic, highly polarized light one should record as a function of time (for each unique machine), the average intensity and wavelength distribution and then derive a composite spectrum. But, this is not an easy task since a high-resolution grating spectrophotometer is not typically available (on the manufacturing floor). The spectral data that does exist (from laser factory and development labs) is available only to a few scanner vendors and laser scientists. For spectral monitoring of its excimer sources in the field,

Cymer has developed an on-board etalon-based instrument, called the Bandwidth Analysis Module (BAM) - however this instrument outputs only FWHM and E95 - not the entire shape of the spectrum.

For this paper we use the term excimer pulse-spectra (EPS) to describe the illumination for a unique exposure system (scanner plus laser) and not just the spectrum for one particular excimer pulse. The plot of intensity vs. wavelength (Figure 2) is easy to interpret even if difficult to obtain in practice. We mention this for the following reason, our research indicates that although numerical spectral approximations[11] such as Lorentzian, modified Lorentzian (mLorentzian), asymmetric Lorentzian, and Gaussian speed-up simulation time (compared to modeling with EPS data) they are not adequately accurate and cannot be used to model several subtle lithographic effects. With next generation TCAD and DFM methodologies concerned with nanometer OPC corrections we feel it is critical to work (simulate) with the most accurate physical description of an excimer laser pulse as possible. Our case studies will highlight the simulation speed and accuracy tradeoff for both spectral approximations and raw EPS data.

Currently, PROLITH v. 9.3.3 includes several CYMER excimer pulse-spectra (EPS) containing ~150 spectral points for both 193nm and 248nm excimer sources (representing a few pm of spectral data). Our current research is focused on lithographic impact studies (iso-dense bias, focus latitude, line-end-shortening, and OPC correction) using unique EPS field signatures (for example, see Figure 2). For simulation/demonstration purposes we like to break the EPS into 3 important regions/metrics of interest. The first metric is called E95. E95 is the spectral width (pm) that contains 95% of the excimer laser energy (for the 193nm excimer laser spectrum shown below in Figure 2, E95 is ~0.23pm). The second region of interest is the tail portion of spectra – the very low level intensity profile extending out +/- 2pm and beyond (a multiple of E95). The third region represents the curvature, K near the pulse neck – the impact on imaging for each zone will be published shortly or by request from Cymer.

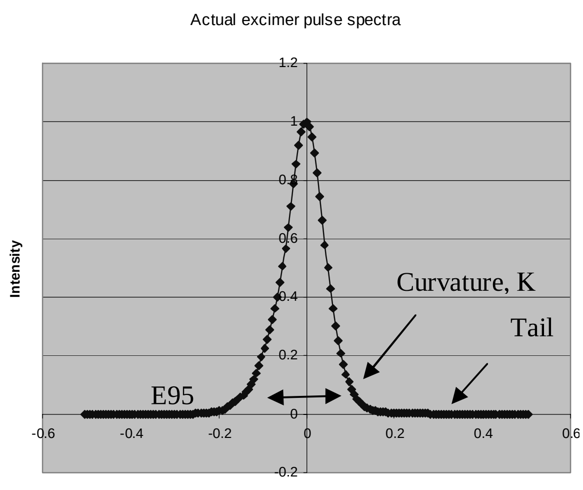

Figure 2: Excimer pulse-spectra (EPS)

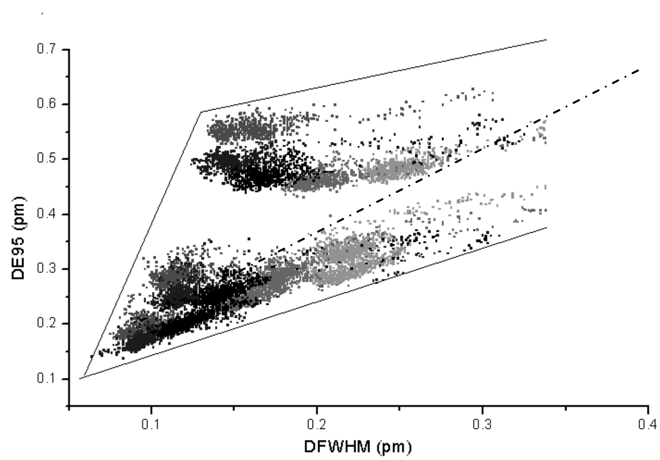

Figure 3: E95 vs. FWHM plot (12000 test points)

2.2 Focus-drilling (Tilted stage, RELAX) and Z-noise

A good reference for the combined effects of focus-drilling for improved (DoF), scanner noise (Z-noise) and excimer bandwidth can be found in the SPIE work by Brunner[11]. An example of focus-drilling for improved lithographic depth of focus is also known as the FLEX process. The process has been described in several papers including the classic paper by Fukuda [12]. PROLITH users have had access to the FLEX method using PROLITH's multi-pass functionality for several years so the method will not be described here again. Recently, attention has been given to the Nikon CDP™ methodology[13] (and EFESE™ from ASML) of tilting the wafer stage during the scan such that each feature receives pulse energy at a range of focus conditions thus producing a scanning, focus-drilling operation similar to the manual FLEX method (using multiple exposure passes). PROLITH v. 9.3.3 now includes this *Focus Averaging* methodology.

Note: to first order, the focus-drilling operation using a tilted wafer stage can be modeled using a top-hat (equal weighting) spectral shape (vide infra).

More recently (2001), Cymer has described a laser driven analog of FLEX called RELAX[2]. The principal idea here concerns exposing the resist using two (or more) different excimer laser pulses (say, half the energy using pulses of type 1 and the other half using pulses of type 2). Here, each laser pulse (type 1 or type 2) would have a center wavelength shifted from nominal wavelength by an appropriate amount (determined by considering: nominal wavelength, NA, pitch, and known chromatic aberrations of the lithographic exposure tool). In effect, the RELAX process performs focus drilling without having to refocus or tilt the stage during exposure. This is also easily simulated using PROLITH version 9.3.3 by simply providing a multi-pulse spectrum (.ill file) and using the new LCA methodology described above. We present a case study below to compare the improvement in DoF for both the RELAX process and tilted stage methodology (NA=0.92 dense contact process using a k1 near 0.35).

Finally, users privy to scanner dynamics or Z-noise files or those using Litel Instruments (ZMAP™) methodology can now enter the random focus (Z) vibrations into PROLITH v. 9.3.3 and study the combined effects of Z-noise with LCAs. Additionally, any combination of the above mentioned focus effects (LCAs, Tilted stage, RELAX, and/or Z-noise) can be simulated (via convolution) using the new functionality in PROLITH.

3. CASE STUDIES

We present three cases studies as mentioned above: 1) Simulating chromatic aberrations with PROLITH v.9.3.3 – speed/accuracy tradeoffs using 2028 spectral points derived from Cymer excimer metrology, 2) comparing the modified Lorentzian spectral approximation with EPS, and 3) DoF enhancement using the tilted stage and RELAX methodologies.

3.1 Speed factor / accuracy tradeoffs using 2028 excimer laser spectral points

For this work we make use of a 2028 point EPS (excimer pulse-spectra) to study the lithographic effects (CD) of longitudinal chromatic aberrations on 193nm imaging using the new PROLITH v. 9.3.3 interface. We compare speed trade-offs (using different speed factors) with the actual point-by-point calculation (summing 2028 aerial images) using speed factor = -1. We then plot results showing the difference in critical dimension. Probably the most important data point for the simulation concerns what value to use for the *Rate of Defocus* or chromatic aberration slope (Λ nm/pm). Back-of-the-envelope calculations using CaF lens data and effective scanner focal lengths yields huge ranges for the slope values (50nm/pm – 1000nm/pm). For this work we used ~400nm/pm which (through our research) we understand to be a typical number for a 193nm imaging system. Since we are interested in the behavior for low k1 processing we simulated the critical dimensions for a 193nm, NA = 0.92 (~k1 =0.28) attn psm, isolated structure.

3.2 Comparing modified Lorentzian with EPS

While several papers[11] point-out that the modified Lorentzian spectral model can be used to approximate an excimer laser spectrum for lithographic simulation we felt it necessary to discuss some subtle points and expand on earlier research. For example, as shown in Figure 3 (above) we plot the E95 vs. FWHM for a range of excimer pulse-spectra derived from Cymer metrology for a wide range (12000 cases) of different excimer operating conditions (rep-rate, duty-cycle, gas mix, etc.) – covering the full machine limits, including conditions well beyond normal operating specifications. In earlier work, Cymer[9] has reported how E95 is a good predictor of the lithographic behavior (iso-dense bias for example) when simulating with excimer pulse-spectra (EPS), although it does not provide a complete description of spectral shape. Clearly, there is not one physical spectral model capable of describing the laser spectrum over the entire range of operation, since this would require the data to fall along a straight line, as illustrated in Figure 3 (dashed line). The two most popular spectral approximations (Gaussian and mLorentzian) are quite different from each other and we expect different lithographic performance (vide infra). As a side note, one can use the Z-noise feature in PROLITH to simulate a Gaussian shaped laser spectrum since the aerial image summation process is identical to that used for LCA or focus-drilling operations.

Again, we present our spectral case study to highlight that for aggressive mask design (the low k1 challenge[14]) we recommend that lithographers explore several different spectral models when trying to approximate excimer pulses using simple shape factors (for example, the exponent and FWHM for the mLorentzian spectra profile). This is simply because a few nanometers of error could be very important – and actual EPS data hard to come by. For example, as shown in Figure 7 (below), we plot a typical EPS Bossung simulation (aerial image) result showing a slightly asymmetric Bossung curve. This asymmetry is expected because the (EPS) spectral data is not perfectly symmetric with wavelength (see Figures 2 and 4 for example) leading to subtle CD through-focus asymmetries and slight shifts in best focus (~ a few nanometers) – obviously, these subtle effects are not accounted for when using a (symmetric) mLorentzian spectral fit (Figure 7). Our current work focuses on multi-parameter models (Gaussian, mLorentzian, asymmetrical Lorentzian), EPS shape, succinct modeling approximations and their impact on lithographic imaging.

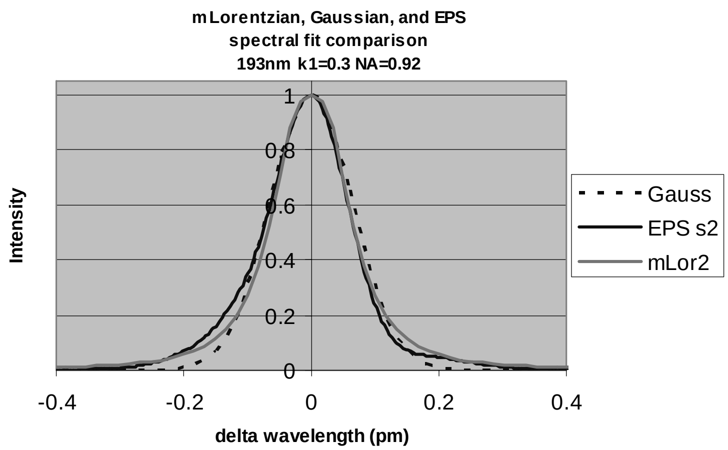

Figure 4: mLorentzian, Gaussian, and EPS data

3.3 DoF enhancement: Tilted stage vs. RELAX

For our final case study we investigate the lithographic improvement in DoF using both the tilted stage (ASML and NIKON) and the RELAX (Cymer) methodologies for a 193nm, k1=0.35 contact-hole process (with an 8% floor for the exposure latitude - EL). For the tilted stage methodology, we ran several through-focus/dose contact-hole simulations using the Focus Range as an independent PROLITH variable in a PPI program to determine an improved DoF for the minimally acceptable exposure latitude. Typically, for 193nm contact hole processes we might need ~1µm of focus range to improve the lithographic DoF; that is, +/- 0.5µm of focus variation during the scan (~100µrad of stage tilt). For the RELAX case, we created 10 *dual pulse* EPS spectral files (vide supra) and ran each spectral file through-focus/dose using PROLITH to find the optimum dual pulse EPS illumination file – the spectral file that yielded the best DoF for the minimal EL.

The tilted stage methodology implemented in PROLITH automatically uses a fixed number of through-focus points to perform the focus drilling operation. Hence, the difference in behavior between the two methods (Figure 9) is effectively due to superimposing different numbers of "out-of-focus" aerial images (mostly near center or nominal wavelength). Subtle details between the two methodologies are available from both Cymer and KLA-Tencor. Note: there are many different variations of the RELAX[2] process and mimicking the tilted stage methodology is easy to simulate with new versions of PROLITH.

4. GRAPHS & RESULTS

4.1 Accuracy and Speed improvements in PROLITH version 9.3.3.14

Shown below in Figure 5 are the results for the first case study where we plot the difference in aerial (and LPM) CD for a 193nm, k1=0.3 semi-isolated line process as a function of speed factor. Speed factor -1 was used as the baseline since when using PROLITH it represents the actual summation of 2028 aerial images - one for each spectral point in the illumination file (12pm spectral range). The excimer pulse spectrum (EPS) was derived from Cymer factory metrology (a portion of the spectra is shown in Figure 2). The run times for each speed factor are shown in Figure 6. It can be seen that if we need to maintain ~0.1nm resolution we certainly need to use speed factor = -1. How many spectral points are actually necessary is the focus of our current research and information is available to Cymer customers.

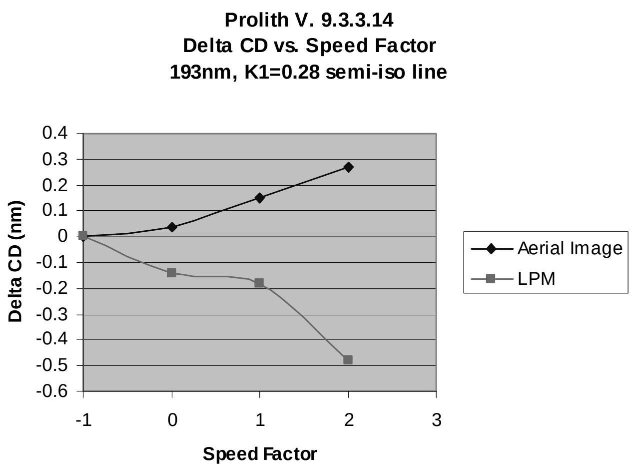

Figure 5: Delta CD (nm) vs. Speed Factor

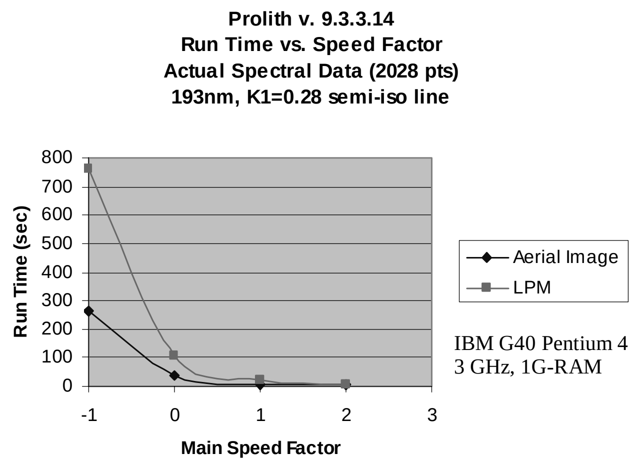

Figure 6: Run Time (sec) vs. Speed Factor

4.2 Side by side comparison: excimer spectra vs. modified Lorentzian

Our second case study involves comparing the simulated CD response (through-pitch and focus) for a low k1 process (k1=0.3, NA=0.92) using spectra derived from raw EPS data and a best fit mLorentzian. The work by Brunner[11] and previous work from Lai[15] discuss EPS spectral curve fitting using purely statistical methods (best fit spectral matching). For this work, we used tuning methods (optimization routines) for spectral modeling – finding the best mLorentzian parameters by minimizing the (through-pitch and focus) CD difference between the simulated EPS spectra and mLorentzian data sets (with considerations for the shape of the 1-d aerial image). A portion of our 2048 point test spectrum is shown in Figure 4 (with E95 ~0.38pm and FWHM ~0.145). When needed, Cymer's high-resolution spectrophotometer enables data acquisition out to +/- 6pm for high accuracy simulation. Figure 4 also shows a mLorentzian spectral fit derived from Cymer EPS data using our tuning method with PROLITH. The mLorentzian spectral curve represents the best fit mLorentzian when considering 3pm (range) of the EPS data. Our optimization procedure (using only +/- 1.5pm of the EPS data) yielded a reasonable spectral fit (R^2 ~0.9) fairly accurate through-pitch and focus results (exp=2.7, FWHM=0.14). Using a larger portion of the EPS spectral tail (+/- 6pm) yielded less accurate spectral fits - currently under investigation. Figure 7 below shows the (asymmetric) through-focus CD simulation results using the EPS data with a spectral range of 3pm and the best fit mLorentzian. Clearly, the out-of-focus condition shows the largest variation – this focus effect is magnified further if we search for problematic pitches in the analysis (Figure 8). While not shown, these effects are further enhanced (~3x) when considering additional spherical aberrations – to be published. We also checked the robustness of the best fit mLorentzian parameters regarding changes in NA and source shape – and initial results indicate similar accuracy.

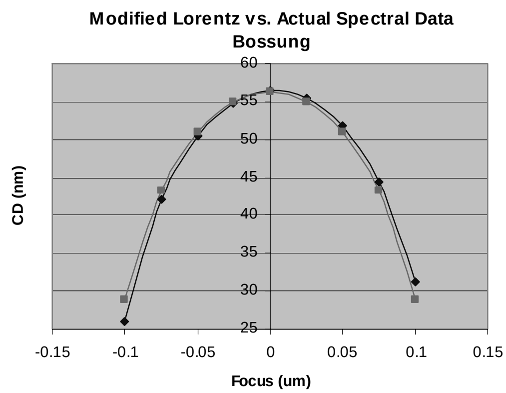

Figure 7: mLorentzian vs. EPS (3pm range) Bossung

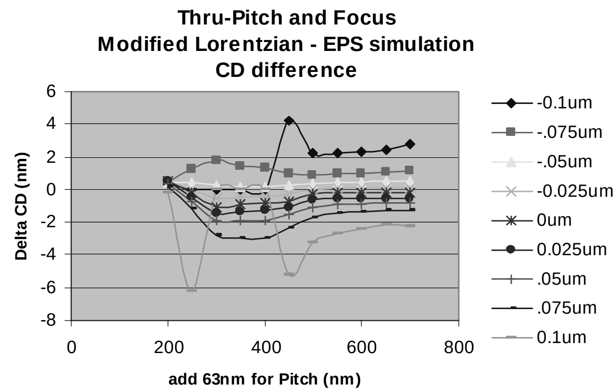

Figure 8: mLorentzian vs. EPS (3pm range) delta-CD

Finally, the authors have created a modified asymmetric Lorentzian to get better Bossung fits but this model requires 4 parameters (2 full wave-half max settings, 2 exponents). Our fitting approach (tuning) compares quite well with direct mLorentzian statistical fits (<nm) when considering +/- 1.5pm of the actual EPS spectra. Our (3pm) Gaussian tuning results were reasonable (CDs within a few nanometers - see Figure 4).

4.3 DoF and EL using RELAX and Stage Tilt methodologies

Shown below in Figure 9 are the EL vs. DoF simulation results for 2 different focus drilling methodologies (RELAX and tilted stage) using PROLITH v. 9.3.3. We found that both methods yielded similar DoF improvements (for example, ~0.5um DoF at 5% EL). The optimum RELAX plot (Figure 9) was derived using two ESP spectra (~E95=0.24pm) separated by ~1pm. RELAX results using impulse spectra (two individual pulses each with 0 bandwidth) showed similar behavior – within ~2%. Note: although not shown below, the authors found some interesting differences in the optimized process window shapes between the 2-pulse RELAX method and the tilted stage methodology - details are available from Cymer or the author.

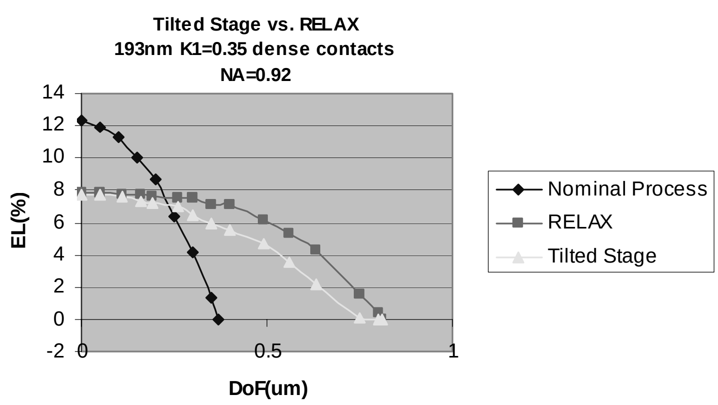

Figure 9: Tilted stage vs. RELAX EL vs. DoF results

5. CONCLUSIONS

5.1 Précis

We presented results for 3 brief simulation case studies using Cymer excimer pulse-spectra (EPS) and PROLITH v. 9.3.3. It was clear that the speed factor settings in PROLITH dramatically impact simulation time as compared to working with large (2028 point) EPS files. Secondly, simulating with the actual EPS data reveals subtle CD differences through-pitch and focus as compared to modified Lorentzian or Gaussian approximations. The authors found that the length of the EPS spectral tail impacts spectral fitting using the mLorentzian spectral approximation (especially if one is concerned with 1nm accuracy). Finally, PROLITH v. 9.3.3 makes it easy to optimize lithographic processes for maximum DoF using either the NIKON CDP (ASML's EFESE) or RELAX focus drilling methodologies. Our simulation and modeling work with excimer pulse-spectra at the 45nm node (and below) shows that understanding the unique field signature for each laser system could be very important when attempting to optimize lithographic processes and masks that require accuracy down to the last few nanometers. We also stress the importance of approximating excimer spectra using several different models and fitting methods to understand the variation in lithographic performance with EPS shape.

In the past, the lithography community relied on Full-Width-Half-Max (FWHM) for simulating lithographic performance of excimer laser sources. More recently, Cymer introduced E95 as an improved metric for pulse performance[9]. Our current work is focused on creating accurate spectral models for high-speed lithography simulation. We stress this point as TCAD and DFM vendors are constantly trying to improve the accuracy and speed of mask design while at the same time simulating larger areas of critical lithographic layers.

5.2 Applications and developments

Our research continues in this area for several reasons. First, as noted above the authors are working on better understanding of how the shape of each unique EPS impacts lithographic performance – especially at the 45nm node and below. Second, we are looking into new methods of approximating excimer pulse-spectra for improved OPC and DFM applications where large area simulation routines are always in need of fast and accurate methodologies and the actual spectra are not currently available.

ACKNOWLEDGEMENTS

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